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UCAC5: New Proper Motions Using *Gaia* DR1

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Abstract

New astrometric reductions of the US Naval Observatory CCD Astrograph Catalog (UCAC) all-sky observations were performed from first principles using the TGAS stars in the 8–11 mag range as the reference star catalog. Significant improvements in the astrometric solutions were obtained, and the UCAC5 catalog of mean positions at a mean epoch near 2001 was generated. By combining UCAC5 with *Gaia* DR1 data, new proper motions were obtained for over 107 million stars on the *Gaia* coordinate system, with typical accuracies of 1–2 mas yr^{-1} (R = 11–15 mag) and about 5 mas yr^{-1} at 16th mag. Proper motions of most TGAS stars are improved over their *Gaia* data and the precision level of TGAS proper motions is extended to many millions more, fainter stars. External comparisons were made using stellar cluster fields and extragalactic sources. The TGAS data allow us to derive the limiting precision of the UCAC x, y data, which is significantly better than 1/100 pixel.

Key words: astrometry – catalogs – proper motions

1. Introduction

The very successful European Space Agency *Gaia* mission is in progress. In 2016 September, the first *Gaia* data were released based on the first 14 months of regular in-orbit operations (Gaia Collaboration et al. 2016a, 2016b). Accurate mean observed positions for the 2015.0 epoch were provided for a total of over 1.1 billion stars down to about magnitude $G = 20.7$, with a median position error of about 1.8 and 1.6 mas for R.A. and decl., respectively (Lindegren et al. 2016). A full 5-parameter (position, proper motion, parallax) astrometric solution was obtained for just over 2 million stars, a subset of about 80% of the *Hipparcos* and Tycho-2 stars. This was achieved by using the *Hipparcos* satellite observations of mean epoch 1991.25 together with the *Gaia* observations to resolve the proper motion and parallax degeneracy. The accuracy of these positions varies as function of magnitude and location on the sky, with a median near 0.3 mas per coordinate and a median error in proper motion of 1.1 and 0.9 mas yr^{-1} for R.A. and decl., respectively (Lindegren et al. 2016).

The U.S. Naval Observatory (USNO) is engaged in producing astrometric star catalogs. The USNO CCD Astrograph Catalog (UCAC) project provided such all-sky data to 16th magnitude with its most recent 4th data release, the UCAC4 (Zacharias et al. 2013). The Tycho-2 catalog (Høg et al. 2000) was used as the reference star catalog for those wide-field CCD observations. Comparisons between the Tycho-*Gaia* Astrometric Solution (TGAS) and Tycho-2 proper motions showed that the latter have large sky-correlated systematic errors of up to a few mas yr^{-1} (Lindegren et al. 2016) due to previously undiscovered large systematic errors in the early epoch Astrographic Catalog data from around 1900, which were used for Tycho-2 proper motions. A re-reduction of the UCAC data using TGAS, as described in this paper, provides a significantly improved product: the UCAC5.

Although the UCAC has positional accuracies not reaching those of the *Gaia* data, the first *Gaia* Data Release (DR1) is lacking proper motion data for all stars fainter than the Tycho-2 limit of about 11th magnitude. The upcoming DR2 release, currently scheduled for early 2018 (Altmann et al. 2017), will change that. New proper motions for about 50 times more stars than are contained in TGAS can now be obtained by combining UCAC data at a mean epoch of 2001 with *Gaia* position data at an epoch of 2015. The accuracy of those proper motions is comparable to those of TGAS up to about $R = 15.0$ and provides valuable additional observations of TGAS stars, which noticeably improves their proper motions.

2. UCAC Re-reduction

2.1. Astrometric Solution

A summary of the relevant features from the UCAC program and data is provided in Table 1. All applicable individual UCAC exposures obtained from Cerro Tololo Interamerican Observatory (CTIO) and the Naval Observatory Flagstaff Station (NOFS) were matched with the *Gaia* TGAS data, which served as the reference star catalog. A new astrometric reduction was performed adopting the systematic corrections of the UCAC x, y data as a function of magnitude. These were previously established using the 2MASS (Skrutskie et al. 2006) data, which covers the full UCAC magnitude range. For more details, please see the UCAC4 paper (Zacharias et al. 2013).

However, the systematic errors as a function of location in the focal plane (the field distortion pattern), as well as the systematic errors as a function of the sub-pixel phase, were re-evaluated and updated using the TGAS residuals separately for the CTIO and NOFS UCAC data set. The distortion pattern is mainly determined by the lens and dewar window, but it also depends on the actual tilt of the focal plane with respect to the optical axis, which will change after disassembly and deployment at a new site. The pixel-phase errors strongly depend on the average width of the image profiles and, thus, also change from site to site.

After applying the new corrections, mean residuals as a function of location in the field of view and sub-pixel phase were reduced to about 2 mas. The new field distortion pattern from the CTIO data is illustrated in Figure 1.

As before, a 6-parameter linear plate model was adopted for the astrometric solution, split into orthogonal (a to d) and

Table 1
Summary of Relevant UCAC Data

astrograph aperture	=	208.0 mm
focal length (f/10)	=	2060.0 mm
image scale	=	100.5 arcsec mm^{-1}
fixed bandpass	=	579 − 643 nm
field of view (lens)	=	9° diameter
number of pixels CCD	=	4k by 4k (Kodak front illum.)
pixel size	=	9.0 micrometer
pixel scale	=	0.905 arcsec/px
field of view CCD	=	1.02 by 1.02 deg
typical FWHM images	=	1.7-2.5 px
observing at CTIO	=	1997-2001 (decl. = −90 to +25)
observing at NOFS	=	2001-2004 (decl. = +25 to +90)
survey pattern	=	2-fold, center-corner
long exposures	=	150 or 125 or 100 s
short exposures	=	1/5 of long exposure
total number of exposures taken = 274,000		
number of acceptable exposures = 218,000		

non-orthogonal parameters (e and f):

$$\xi = ax + by + c + ex + fy$$

$$\eta = -bx + ay + d + fx - ey.$$

Here, ξ, η are the standard coordinates (scaled from radian to arcsec) and x, y are the observed center coordinates of star images on the CCD (scaled from pixel unit to arcsec).

Figure 2 shows the distribution of the number of reference stars used per individual UCAC exposure. The mean is about 50, corresponding to the average sky density of the TGAS catalog and the UCAC 1.0 square degree field of view. The astrometric solution errors are presented in Figure 3, in separate panels for the short and long exposure. These errors include the x, y center errors of the observed image profiles, the reference star catalog errors, and the error contribution from the turbulent atmosphere. The latter scales inversely with the square-root of the integration time and, apparently, is a significant contribution for the short exposures. The same is shown for the UCAC4 data in Figure 4. The vast improvement using (almost) error free TGAS reference stars is striking, showing the high precision of the UCAC observations, which were previously overshadowed by the Tycho-2 reference star errors.

Figure 5 shows residuals as a function of calibrated UCAC bandpass magnitude for CTIO data. This is likely the largest remaining contribution to systematic errors in the UCAC data, caused by the poor charge-transfer efficiency (CTE) of that particular detector (Zacharias et al. 2004). No attempt to improve the model was made here, because the TGAS reference stars have a limiting magnitude of about 11.5, while the UCAC data reaches beyond 16th magnitude.

2.2. Positions

Using the model described above, the positions of all observed objects were obtained at their epoch of observation for all applicable CCD exposures. Figure 6 shows the mean observed epoch as a function of declination. The UCAC survey began in the south and ended at the north celestial pole.

Mean observed UCAC5 positions were obtained from a weighted mean of the individual positions (images). Outliers were rejected as much as possible considering the small number of observations available for this task. Figure 7 shows the distribution

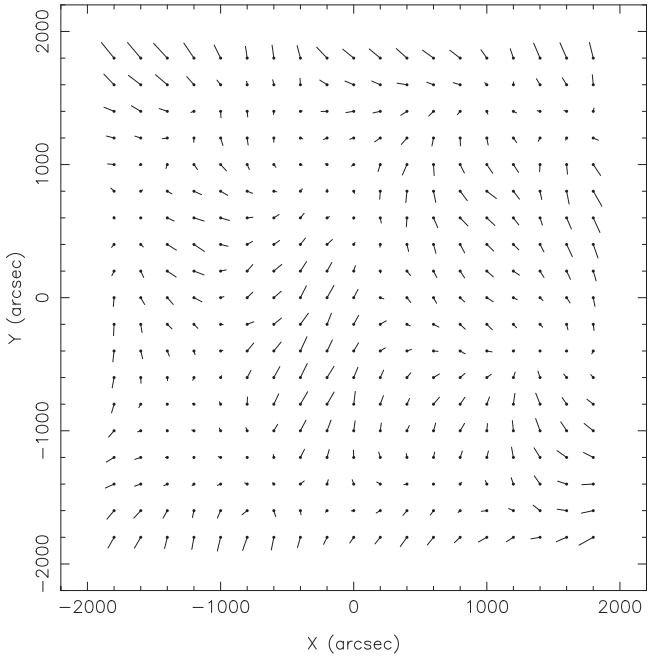


Figure 1. Field distortion pattern of the UCAC instrument from TGAS reference star residuals of all applicable exposures taken at CTIO. The vectors are scaled by a factor of 5000. The largest residual vectors are about 25 mas long.

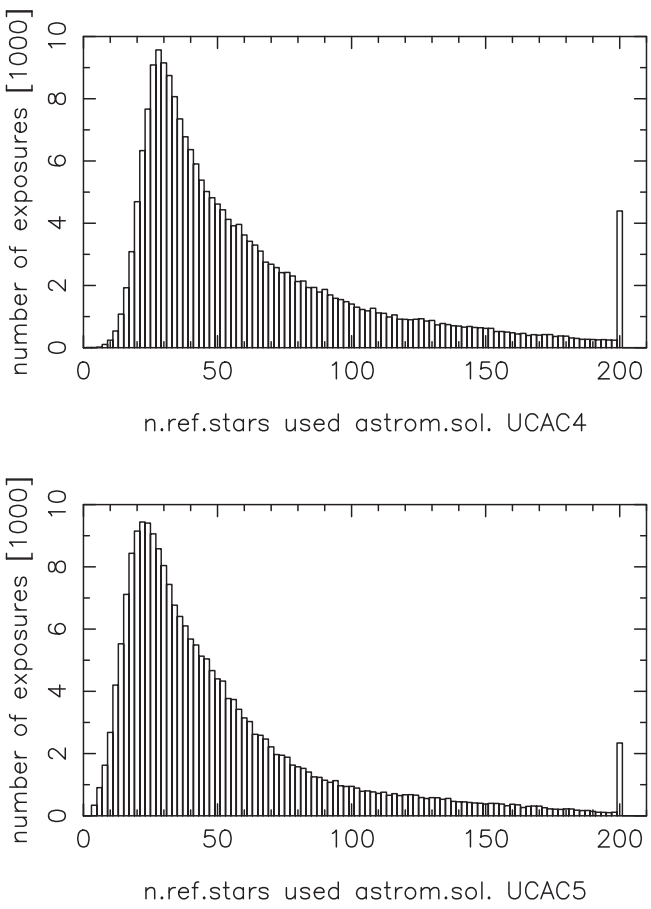


Figure 2. Distribution of the number of reference stars used in the UCAC4 (top) and UCAC5 (bottom) astrometric reductions (TGAS stars) per individual exposure. The last bin sums up all exposures with 200 and more reference stars.

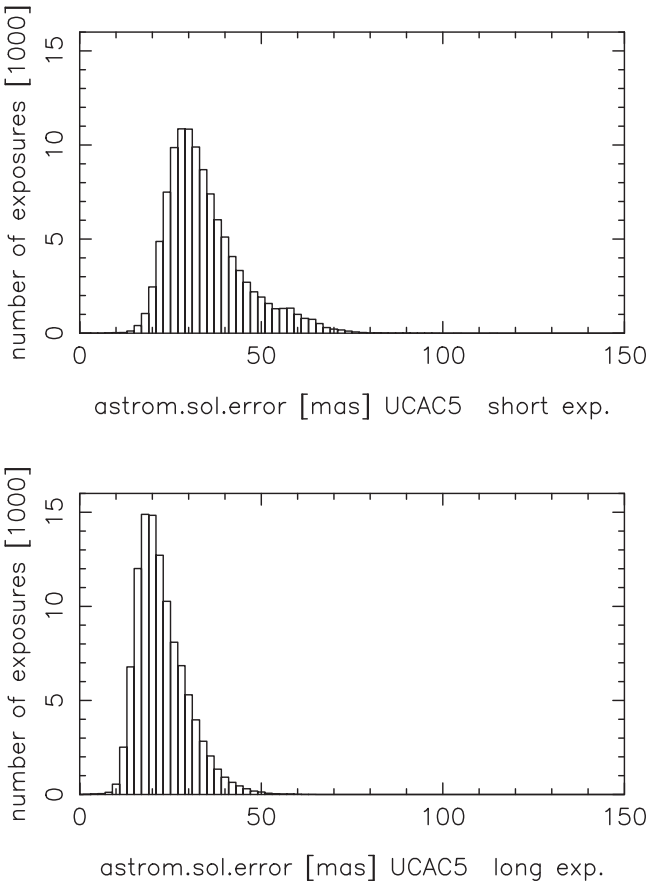


Figure 3. Distribution of astrometric solution error of UCAC5 individual exposures using TGAS reference stars and the new systematic error model. Top: results for the short exposures (20, 25, 30 s) are shown. Bottom: results for the long exposures (100, 125, 150 s) are shown.

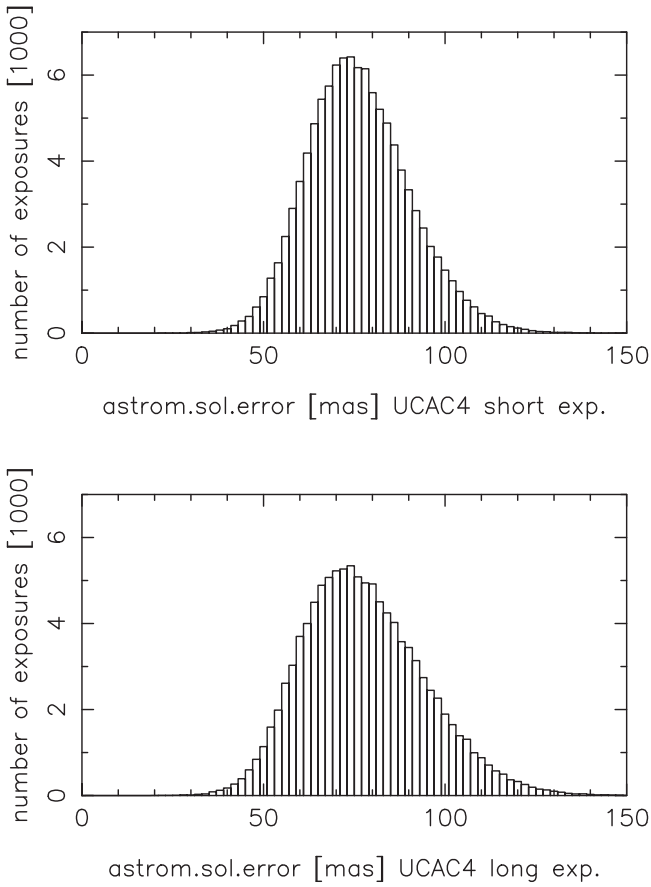


Figure 4. Same as the previous figure but for the UCAC4 results using Tycho-2 reference stars.

of the number of observations used for the mean positions. In cases with a total of 2 images that display discrepant positions, the outlier can not be identified, and an unweighted mean position is given with the number of used images set to zero.

Due to the small field of view and the desire to cover all-sky, the number of observations per star is small. A 2-fold (center-in-corner) overlap pattern was adopted, with a short and long exposure on each field to extend the dynamic range. Thus, stars in the 8–9.5 mag range typically have 2 images (from the short exposures only), stars in the 9.5 to ≈14.5 mag range usually have 4 images (short and long exposure), while stars fainter than about $R = 14.5$ show up only on the long exposures.

The errors on the UCAC5 positions were obtained from the formal errors (x, y center errors plus astrometric solution error propagation) of the individual images used for the mean position. A 10 mas term was added in quadrature to account for possible remaining systematic errors and to provide a more realistic error floor for the small number statistics of individual stars. This error floor is likely dominated by the remaining systematic errors as a function of magnitude, and the same value that was used in the earlier UCAC4 reductions was adopted here, because no changes in the calibration model for those errors were made.

2.3. Adding NOMAD Data to Gaia DR1

The Naval Observatory Merged Astrometric Data set (NOMAD) catalog (Zacharias et al. 2005) contains about a billion entries, and it covers all-sky and the magnitude range from naked eye stars to about $V = 20$ mag. It contains positions, proper motions, and optical and near-IR magnitudes. NOMAD positions were updated to the 2015 epoch using its proper motions and then matched to the *Gaia* DR1 data. Over 638 million sources were matched within 1 arcsec based on position only. A new internal catalog was created that adds NOMAD data, if available, to all sources in *Gaia* DR1.

These new proper motions are of value for stars not contained in the UCAC data, thus, mainly for stars fainter than about $R = 16$ mag. The new proper motion data for stars in common with UCAC data are very helpful to correctly match UCAC stars to the *Gaia* data, particularly for stars with moderate to large proper motions (see below).

3. Results

3.1. Position Error Analysis

Having results from largely different exposure times allows us to determine the individual error contributions of the UCAC observations. The astrometric solution error, σ_S, has 3 components: the errors of the reference star catalog σ_r at epoch of observations, the x, y data error σ_{xy}, and the error introduced by the turbulence in the atmosphere, σ_a,

$$\sigma_S^2 = \sigma_r^2 + \sigma_{xy}^2 + \sigma_a^2$$

The variance of the error contribution from the atmosphere scales inversely with exposure time, t,

$$\sigma_a^2 = \sigma_0^2/t$$

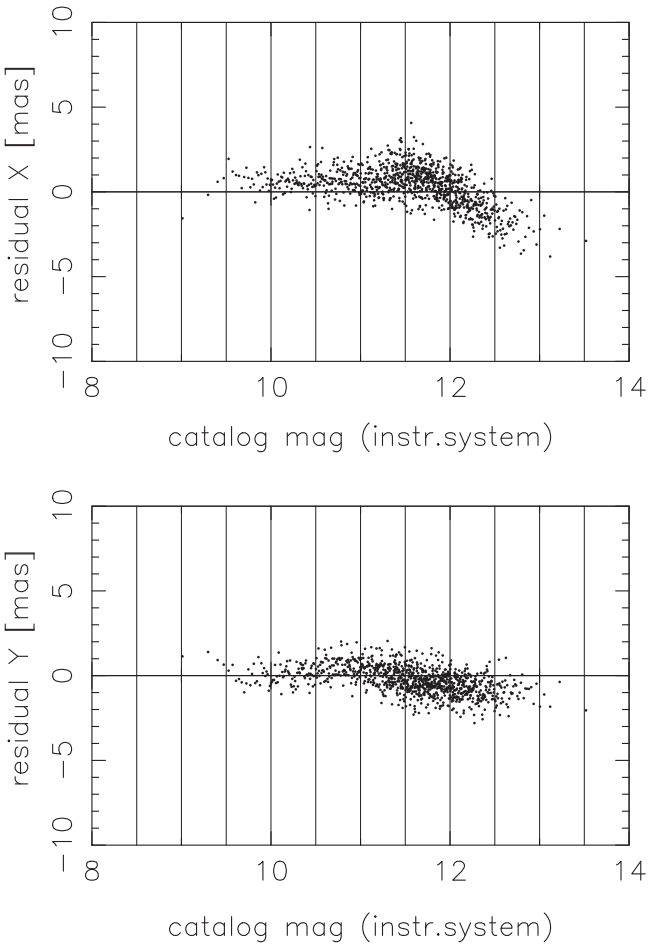


Figure 5. UCAC5 residuals (along x = R.A. top, along y = decl. bottom) as a function of calibrated UCAC bandpass magnitude from data taken at CTIO (long and short exposures together). Each dot is the mean of 5000 residuals.

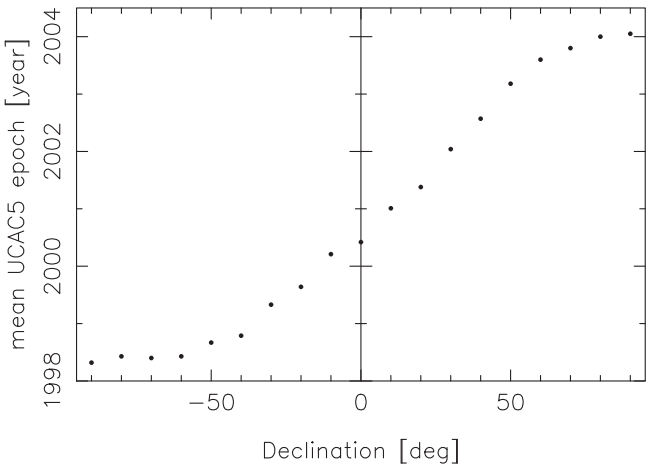


Figure 6. UCAC5 mean observing epoch as a function of declination.

while the other 2 error contributions are independent of exposure time. The reference star errors in the magnitude range used here (mostly $G = 9$–11) are mainly a function of epoch (see below), and the x, y errors are nearly constant for these high S/N data. We define

$$\sigma_c^2 = \sigma_r^2 + \sigma_{xy}^2$$

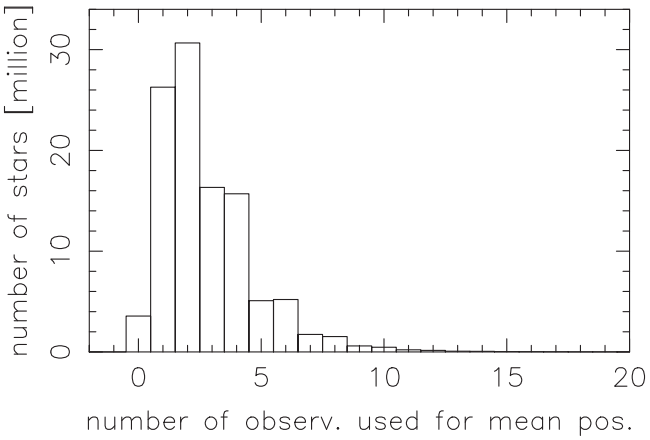
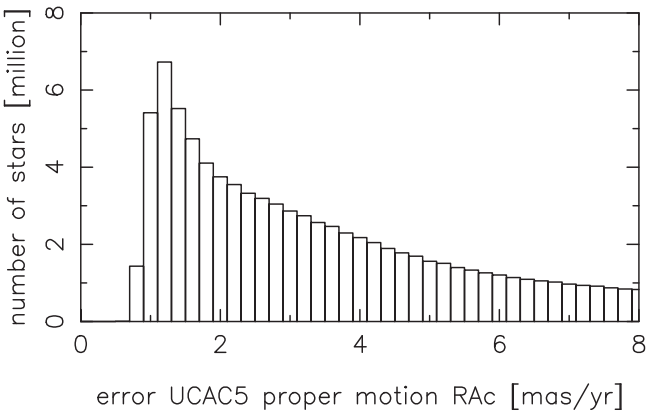


Figure 7. Distribution of the number of observations (individual exposures) used for the mean UCAC5 position. See the text for objects in the zero bin.



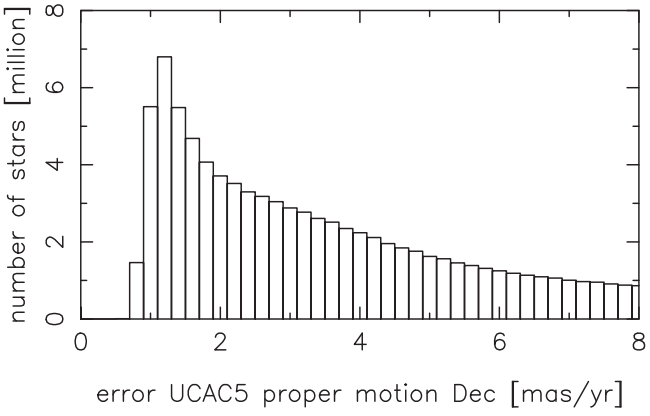


Figure 8. Distribution of errors in proper motion of our UCAC5-*Gaia* catalog (R.A. on top, decl. on the bottom).

leading to

$$\sigma_S^2 = \sigma_c^2 + \sigma_0^2/t$$

For 2 different exposure times, we thus have 2 linear equations with known σ_S, which allows us to directly solve for σ_c, and σ_0. From Figure 3, we see the peaks of the UCAC5 astrometric solution errors, σ_S at 29 mas for the short exposures (on average 25 s), and 19 mas for the long exposures (on average 125 s). The peak values of these distributions can be interpreted as "typical good quality" observations. With these numbers, we get $\sigma_0 = 122$ mas s$^{1/2}$, the error contribution from

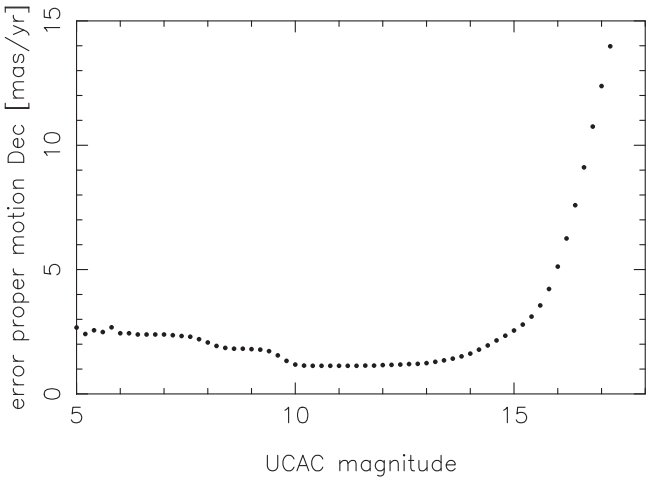


Figure 9. Errors of proper motions of the UCAC5-*Gaia* catalog as function of UCAC magnitude.

Table 2
Data Columns of UCAC5 Catalog

Column	Name	Unit	Description
1	srcid		*Gaia* source ID
2	flg		1 = TGAS, 2 = not TGAS, in UCAC, 3 = other in NOMAD
3	nu		number of images used for mean position
4	epoc	1/1000 year	mean UCAC epoch (after 1997.0)
5	ira	mas	mean UCAC R.A. at epoch (item 4)
6	idc	mas	mean UCAC decl. at epoch (item 4)
7	pmra	0.1 mas yr^{-1}	proper motion R.A.*cos decl.
8	pmdc	0.1 mas yr^{-1}	proper motion decl.
9	pmer	0.1 mas yr^{-1}	formal error of proper motion R.A.
10	pmed	0.1 mas yr^{-1}	formal error of proper motion decl.
11	gmag	mmag	*Gaia* DR1 *G* magnitude
12	umag	mmag	mean UCAC model magnitude
13	Rmag	mmag	photographic *R* magnitude (NOMAD)
14	Jmag	mmag	2MASS *J* magnitude
15	Hmag	mmag	2MASS *H* magnitude
16	Kmag	mmag	2MASS *K* magnitude

the atmosphere, and $\sigma_c = 15.5$ mas, the rms combined error of the reference stars and the x, y centroiding error.

The reference star errors at the mean UCAC epoch of 2001 are dominated by proper motion errors. From Lindegren et al. (2016), we see that, for TGAS stars not in the *Hipparcos* sample, the median proper motion errors are about 1.1 and 0.9 mas yr^{-1} for the R.A. and decl. components, respectively. Assuming 1.0 mas yr^{-1} here and an average epoch difference of 14 years between the UCAC and the TGAS positions, we have an estimate of $\sigma_r = 14$ mas. This allows us to solve for the last remaining error contribution, $\sigma_{xy} = 6.7$ mas.

This error includes random centroiding errors as well as remaining uncorrected systematic errors, e.g., errors as a function of pixel phase, location in the field of view, and magnitude (over the range of the reference star magnitudes). Note that σ_{xy} is the average position error of high S/N UCAC observations per coordinate and per exposure (which is 1/135 pixel). Assuming that the error contributions of the reference stars and those of the atmosphere are small, the obtained observational precision is then limited by σ_{xy}. The former will soon be obtained with the 2nd

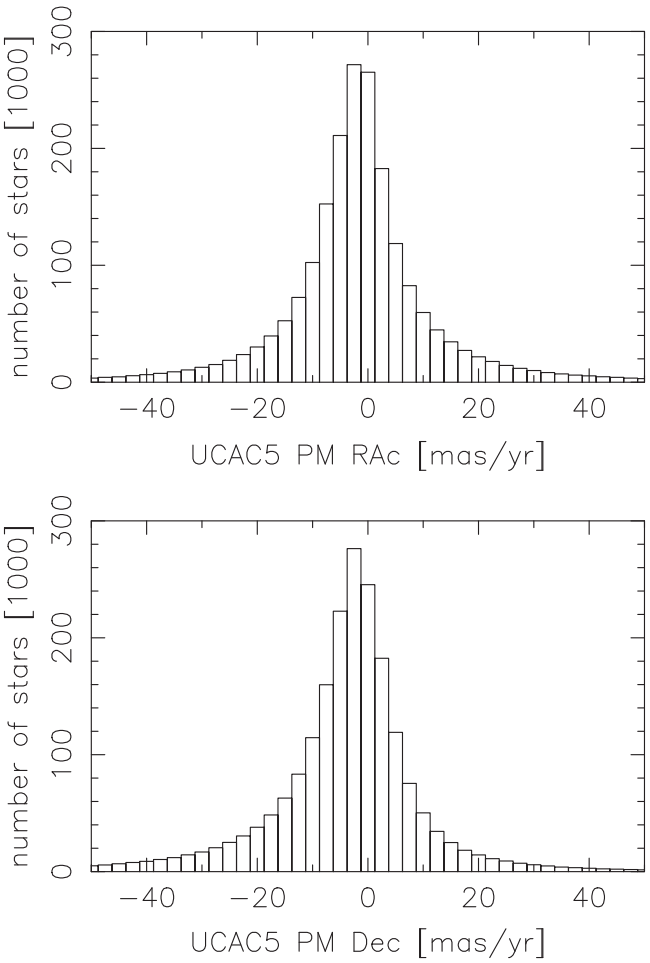


Figure 10. Distribution of UCAC5 proper motions of stars in common between UCAC5 and TGAS, for R.A. (top), and decl. (bottom).

Gaia data release, and the latter can be achieved with long integration times.

The image center algorithm used to derive the UCAC x, y data from the pixel data is a weighted least-square fit with a two-dimensional Gaussian model followed by extensive empirical modeling of the pixel-phase and other systematic errors. No elaborate PSF fitting was performed; instead, the high precision was obtained by analyzing and modeling the position residuals. Details are described in Zacharias et al. (2004).

3.2. UCAC5– Gaia Proper Motions

The *Gaia* plus NOMAD data catalog positions were propagated to a mean epoch of 2001 and then matched with the UCAC5 observational catalog. Again, a match was assumed if the position difference was within 1 arcsec in each coordinate. This resulted in 107.7 million stars in common between the UCAC and *Gaia* data. New proper motions were calculated for all those stars based on the 2 epoch positions (*Gaia* at 2015 and UCAC5 at about 2001), with a mean epoch difference of about 14 years. No NOMAD positional data were used for these proper motions. The NOMAD data only served to facilitate the proper match, thus, also providing results for stars with large proper motion.

Errors of the proper motions were obtained from the formal position errors of *Gaia* and UCAC5 and the epoch difference of individual stars. Figure 8 shows the distribution of the proper

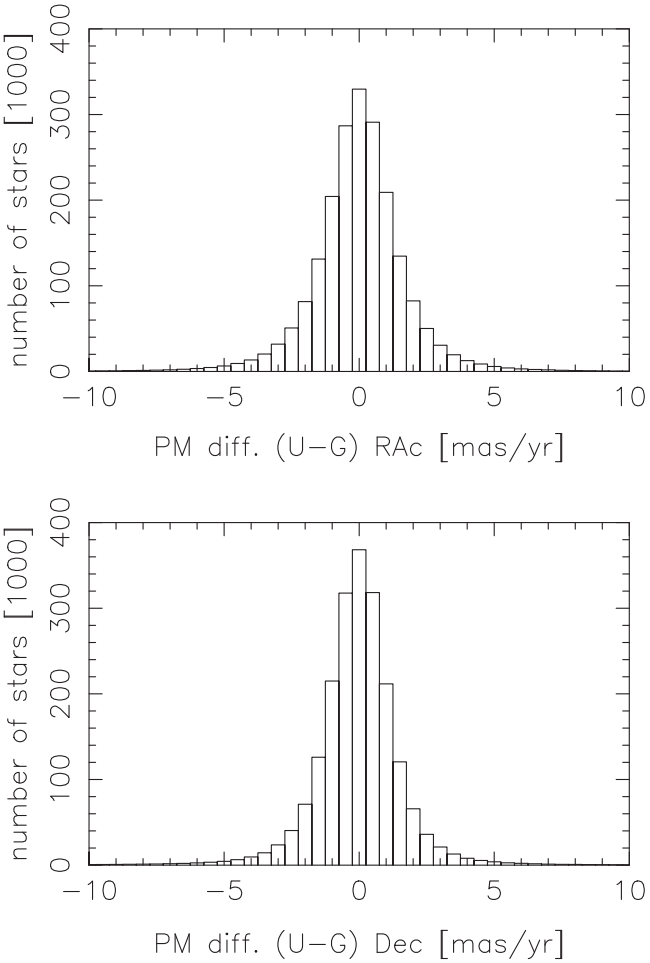


Figure 11. Differences between TGAS and UCAC5 proper motions for R.A. (top) and decl. (bottom).

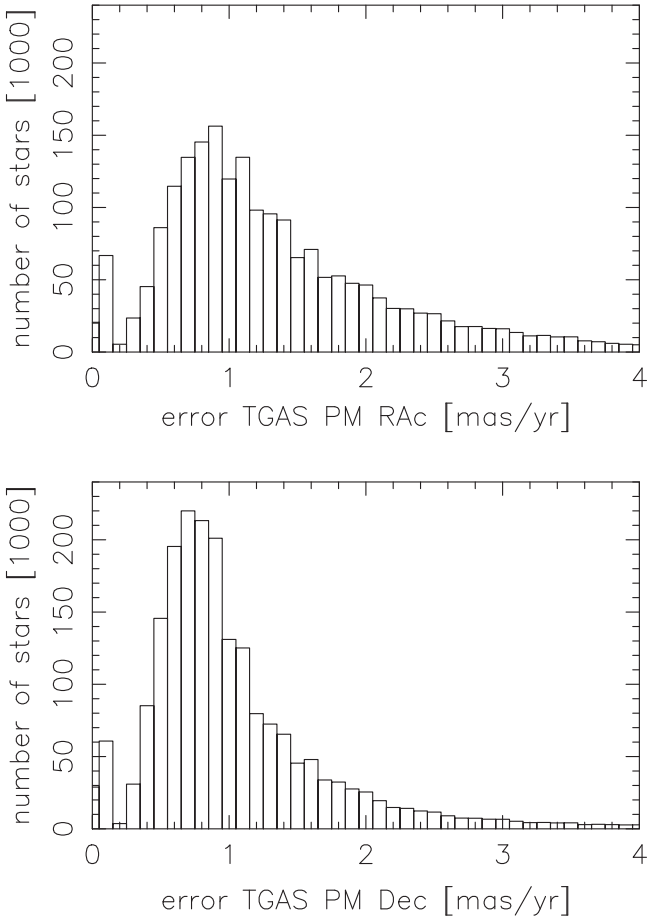


Figure 12. Formal errors of TGAS proper motions of stars in common between UCAC5 and TGAS, for R.A. (top), and decl. (bottom).

motion errors. This distribution peaks at about 1.2 mas yr^{-1}, which is comparable to the TGAS proper motion errors but for many millions of more stars.

Figure 9 shows the strong dependence of our proper motion errors with brightness. Errors in proper motion slowly increase to 2.5 mas yr^{-1} at about magnitude 15 and then rapidly increase to about 10 mas yr^{-1} at the limiting magnitude of 16.5 due to the low S/N of faint stars.

Table 2 lists the data items of our UCAC5 catalog. Positions are given at the mean UCAC observed epoch for each star on the *Gaia* reference frame. The UCAC5 binary data file, sorted by declination is 4.3 GB large and will be available from the Centre de Données astronomiques de Strasbourg (CDS).

3.3. Close Doubles

A match of UCAC5 with itself was performed, revealing some 52,000 multiple matches within 2 arcsec. Spot checks indicate 2 types of cases. The first case is defined by close pairs in *Gaia* DR1, i.e., 2 real stars that are matched to the same UCAC observation or the photocenter of the pair, which is unresolved in the UCAC data. The second case is defined by close doubles that are seen as 2 stars in both *Gaia* and UCAC data. No stars identified in this investigation were removed from the published catalog. The *Gaia* DR1 source identifier remains unique within the UCAC5 catalog, because the DR1 entries were used as the initial input list. However, in a few cases, the same UCAC object is matched to 2 different DR1 entries. No duplicate entries, i.e., entries with positions identical to within a few mas, were found in UCAC5.

3.4. Comparison to TGAS

A separate formatted data file is available for the 2,054,491 stars in common between TGAS and UCAC5, which also lists the differences in proper motion (UCAC5–TGAS). The TGAS proper motions use the *Gaia* observations (at epoch 2015) together with the *Hipparcos* observations of these stars (at epoch 1991). The UCAC5 proper motions are based on the astrograph observations at a mean epoch of about 2001 and the *Gaia* 2015 observations. Of course, these proper motions are somewhat correlated as both use the same later epoch data but different early epoch observations. Furthermore, the UCAC5 data uses TGAS stars as reference stars, which include use of TGAS proper motions. However, the UCAC5 epoch observations are largely independent new observations due to the fact that typically 20–200 such reference stars are used in the astrometric solutions of UCAC observations with a simple linear model of 6 parameters, which provides a large degree of over-determination in the least-squares reductions.

The distribution of UCAC5 proper motions is shown in Figure 10. The distribution of the differences in proper motions are small (Figure 11). The formal errors of proper motions for stars in common are shown in Figures 12 and 13 for the TGAS

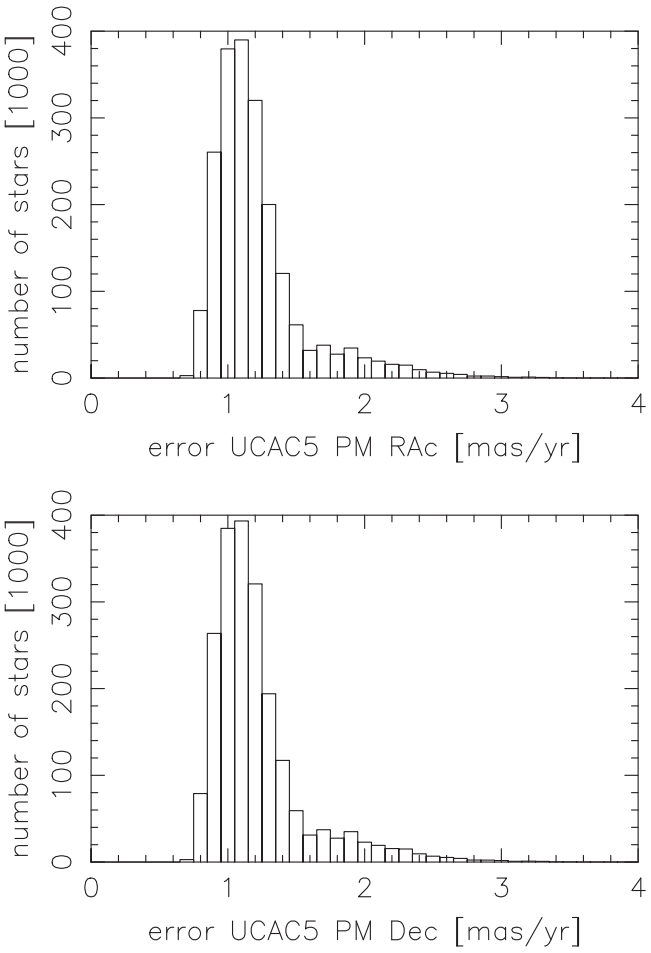


Figure 13. Formal errors of UCAC5 proper motions of stars in common between UCAC5 and TGAS, for R.A. (top), and decl. (bottom).

and UCAC5 data, respectively. Both proper motions are similar in performance. TGAS has more stars with about 1 mas yr^{-1} or less errors, while the UCAC5 proper motions are somewhat better for stars with about 2 mas yr^{-1} TGAS proper motion errors and above.

4. External Comparisons

4.1. Star Cluster

As an example of astrophysical application and validation of the UCAC5 proper motions, 2 cluster areas were picked with a box size of 30 arcmin. In Figure 14, UCAC5 proper motions of all such stars in the open cluster NGC 3532 area are shown in comparison to the 4th release of the Southern Proper Motion (SPM4) program (Girard et al. 2011) proper motions, the previous "gold standard" for absolute proper motions of faint stars. Figure 15 shows the same for the area around the globular cluster NGC 6397. A significant improvement in the ability to separate cluster member stars from non-cluster stars is seen with the UCAC5 proper motions as compared to the SPM4 proper motions.

4.2. Extragalactic Sources

Due to their extreme distance, extragalactic sources will have negligible proper motions. Thus, the observed proper motions show the limitations of the catalog data. A match of UCAC5

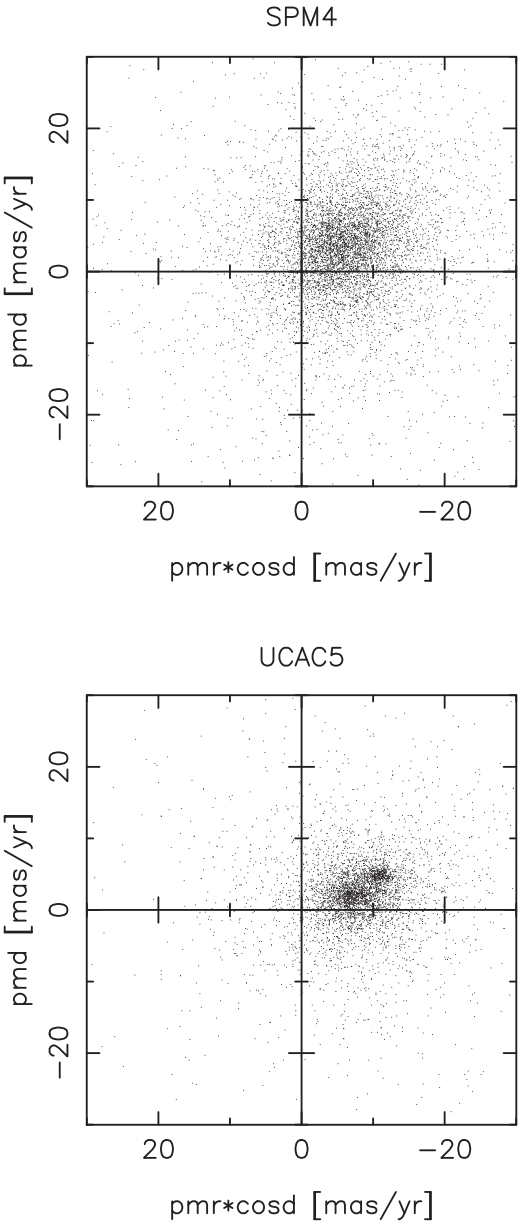


Figure 14. SPM4 (top) and UCAC5 (bottom) proper motions (pmr = along R.A., pmd = along decl.) of stars in common between UCAC5 and SPM4 in the 30 arcmin area around the open cluster NGC 3532.

with LQAC3 (Souchay et al. 2015) was performed, which lists over 321,000 confirmed extragalactic sources, mostly QSOs. A total of 2001 LQAC3 sources are in common with the UCAC5 within 1.5 arcsec.

Table 3 summarizes results for selected subsets, per coordinate and for the proper motions in mas yr^{-1} as well as for their normalized values (proper motion divided by formal error of the proper motion of that object). Subsets were selected by minimum number of UCAC observations used for the mean UCAC5 position (nu), the LQAC3 catalog object type (R = astrometric radio source, Q = QSO, others include AGN and BL-Lac objects), the UCAC5 bandpass mean observed magnitude (mag), and the redshift z. The total number of objects for each set is also given, while 80% of these are used to derive the mean and rms results, excluding the top and bottom 10% of the data after sorting (to prevent outliers from affecting this analysis). The entry "all" in

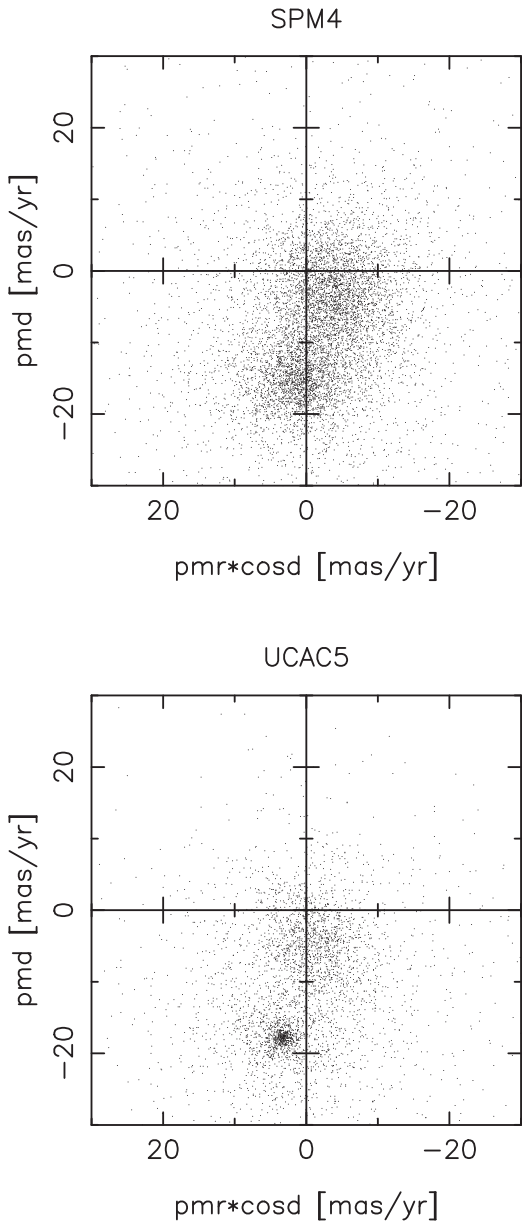


Figure 15. SPM4 (top) and UCAC5 (bottom) proper motions (pmr = along R.A., pmd = along decl.) of stars in common between UCAC5 and SPM4 in the 30 arcmin area around the globular cluster NGC 6397.

Table 3 means no restriction has been applied for that particular column item. The last 2 lines in Table 3 list results for sources in common with the 2nd version of the International Celestial Reference Frame (ICRF2). The ICRF2 (Fey et al. 2009) currently defines the inertial coordinate system on the sky and is derived from highly accurate radio very long baseline interferometry, observations of compact, extragalactic sources.

For most data sets, a small negative offset in the mean UCAC5 proper motions of about -0.5 mas yr^{-1} is seen, while the ICRF sources do not show this. The rms scatter of the observed proper motions is larger than the formal errors for most data sets. However, when excluding low redshift sources, the rms scatter is somewhat reduced.

5. Discussion and Conclusions

Until now, high quality ground-based observations to obtain positions were impacted by relatively poor reference star data. The TGAS catalog now shows the full potential of such observations. Future *Gaia* data that have even more accurate positions and for many more, fainter stars will have a big impact on such ground-based observations, e.g., in time-domain astronomy. The quality of the telescope and instrument will be more important than ever before. The limitation of the USNO redlens astrograph data can be expected to be significantly below 1/100 of a pixel per coordinate for single long exposure observations of high S/N stars.

The UCAC5 positions on the *Gaia* coordinate system provide additional data of similar quality to the *Hipparcos* mission Tycho star observations and, thus, have the potential to improve the TGAS proper motions. UCAC5 provides new accurate proper motions for millions of more stars that are fainter than TGAS, which will allow astronomers to have a preview into research that will only be possible with the next *Gaia* data release. At the faint end, UCAC5 proper motion errors are relatively large due to the low S/N of these observations. Better proper motions for stars fainter than about 15th mag are available from proper motions obtained by combining NOMAD with *Gaia* DR1 (catalog of 503 million stars is available upon request), or the recently published PPMXL re-reduction, called the HSOY (Altmann et al. 2017) catalog.

The biggest issue with the UCAC5 data is still the problematic corrections of systematic errors as a function of magnitude due to the poor CTE of the CCD used in the

Table 3
UCAC5 Proper Motions of Extragalactic Sources from LQAC3

nu	Obj.	mag	z	Total	Mean (mas)		rms (mas)		Norm. Mean		Norm. rms	
$\geqslant$	Type	$\leqslant$	$\geqslant$	n.obj.	μ_α	μ_δ	μ_α	μ_δ	μ_α	μ_δ	μ_α	μ_δ
2	all	all	all	1108	−0.42	−0.70	4.59	4.53	−0.11	−0.20	1.14	1.11
2	R,Q	all	all	461	0.05	−0.39	3.76	4.20	0.02	−0.12	0.87	0.99
2	all	15.8	all	541	−0.99	−0.99	4.88	4.34	−0.32	−0.33	1.58	1.48
2	R,Q	15.8	all	167	−0.83	−0.31	3.74	3.87	−0.24	−0.13	1.36	1.42
2	R,Q	all	0.5	180	−0.21	−0.08	4.06	4.50	−0.04	−0.06	0.94	1.00
2	all	all	0.5	184	−0.22	−0.09	4.14	4.50	−0.03	−0.07	0.96	1.00
1	ICRF	all	all	184	0.17	0.37	4.64	4.45	0.05	−0.01	0.81	0.81
2	ICRF	all	all	124	0.01	0.28	3.20	3.39	0.02	−0.03	0.86	0.86

program. However, the remaining systematic positional errors are expected not to exceed 10 mas over the entire magnitude range of UCAC data (verified with TGAS data for the 8–11 mag range), which can lead to systematic errors in the UCAC5 proper motions up to 0.7 mas yr^{-1}. This is confirmed with comparisons to extragalactic sources.

Restricting the sample of extragalactic sources to redshift of 0.5 or higher results in a reduction in the UCAC5 observed proper motion scatter. This is another indication that possible optical structure of nearby extragalactic sources is affecting the observed image centers. Both epochs (UCAC and *Gaia*) used for these proper motions are based on optical data; however, the resolution of *Gaia* is at least 10 times higher than that of the astrograph. It appears that both instruments "see" a different photocenter, at least for cosmological nearby sources, resulting in a larger scatter of the proper motions despite the fact that they are typically brighter with smaller formal position errors than more distant sources.

We used the PostgreSQL Q3C sky-indexing scheme for some of our external catalog comparisons (Koposov & Bartunov 2006), as well as the Department of Defense Celestial Database of the USNO Astrometry Department, developed by V. Makarov, C. Berghea, and J. Frouard. Pgplot by California Institute of Technology was used to produce plots. The gfortran and g77 compilers were used for code development. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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